

hep-ph/0103008
 KEK-TH-744
 IPAS-HEP-2001-02
 February 2001

Effect of Supersymmetric phases on the Direct CP Asymmetry of $B \rightarrow X_d \gamma$

A.G. Akeroyd^{1*}, Y.-Y. Keum^{2†} and S. Recksiegel^{1‡}

¹ *Theory Group, KEK, Tsukuba, Ibaraki 305-0801, Japan*

² *Institute of Physics, Academia Sinica,
 Nankang, Taipei, Taiwan, 11529, R.O.C.*

Abstract

We investigate the effect of supersymmetric CP violating phases on the inclusive decay $B \rightarrow X_d \gamma$. Although such a decay contains a large background from $B \rightarrow X_s \gamma$, if isolated it may exhibit sizeable CP violation, both in the Standard Model (SM) and in the context of models beyond the SM. With unconstrained supersymmetric CP violating phases we show that the direct CP asymmetry (\mathcal{A}_{CP}) lies in the region $-40\% \leq \mathcal{A}_{CP} \leq 40\%$, where a positive asymmetry would constitute a clear signal of physics beyond the SM. Even if a direct measurement of $B \rightarrow X_d \gamma$ proves too difficult experimentally, its asymmetry contributes non-negligibly to the measurements of \mathcal{A}_{CP} for $B \rightarrow X_s \gamma$, and thus should be included in future analyses. We show that there may be both constructive and destructive interference between $\mathcal{A}_{CP}^{d\gamma}$ and $\mathcal{A}_{CP}^{s\gamma}$.

Keywords : CP Asymmetry, Rare B decay, SUSY CP violating phases

*akeroyd@post.kek.jp

†keum@phys.sinica.edu.tw

‡stefan@post.kek.jp

1 Introduction

Theoretical studies of rare decays of b quarks have attracted increasing attention with the recent turn-on of the B factories at KEK and SLAC [1],[2]. In this paper we are concerned with the rare decay $b \rightarrow d\gamma$ which proceeds via an electromagnetic penguin diagram, and is sensitive to the CKM matrix element V_{td} . The latter is so far unmeasured directly and in the Wolfenstein parameterisation is given by:

$$V_{td} = A\lambda^3(1 - \rho - i\eta) \quad (1)$$

By assuming unitarity of the CKM matrix and using various experimental data ($\epsilon_K, |V_{ub}/V_{cb}|, \Delta m_d, \Delta m_s$) an allowed region for ρ and η at 95% c.l. [3] can be obtained. This enables one to infer the range of V_{td} consistent with the unitarity of the CKM matrix.

A direct measurement of V_{td} is thus desirable and we will be considering the inclusive decay $B \rightarrow X_d\gamma$. Current measurements of $B_d^0 - \overline{B}_d^0$ mixing yield $0.0065 \leq |V_{td}V_{tb}^*| \leq 0.010$ [4], where the main source of error is the theoretical uncertainty in the hadronic matrix element $f_{B_d}\sqrt{B_{B_d}}$. Alternative ways to measure the ratio $|V_{td}/V_{ts}|$ have been proposed and include the $B^0\overline{B}^0$ mixing ratio $\Delta m_d/\Delta m_s$ and the ratio of the branching ratios (BR) of $B \rightarrow X_sl^+l^-$ and $B \rightarrow X_dl^+l^-$ [4].

The short distance contribution to $B \rightarrow X_d\gamma$ is the quark transition $b \rightarrow d\gamma$. Estimates for the long distance contributions can be found in [5, 6] and their relative size is expected to be around 10% of the short distance contribution. Experimental upper limits exist for the branching ratios (BRs) of the exclusive decay channels, $B \rightarrow \rho^0\gamma$ and $B \rightarrow \rho^+\gamma$. CLEO [7] obtains $\leq 1.7 \times 10^{-5}$ and $\leq 1.3 \times 10^{-5}$ respectively, with corresponding measurements by BELLE [8] of $\leq 0.56 \times 10^{-5}$ and $\leq 2.27 \times 10^{-5}$.

There is considerable motivation for calculating the BR and CP asymmetry (\mathcal{A}_{CP}) of the inclusive channel $B \rightarrow X_d\gamma$:

- (i) It provides a theoretically clean way of measuring V_{td} , as proposed in [9, 10]
- (ii) \mathcal{A}_{CP} in the SM is sizeable, and much larger than that for $b \rightarrow s\gamma$ [10].
- (iii) \mathcal{A}_{CP} is sensitive to new physics which contributes to C_7 [11, 12, 13, 14].
- (iv) The current measurement of \mathcal{A}_{CP} for $b \rightarrow s\gamma$ by the CLEO Collaboration [15] is sensitive to events from $b \rightarrow d\gamma$. Therefore knowledge of \mathcal{A}_{CP} for $b \rightarrow d\gamma$ is essential, in order to compare experimental data with the theoretical prediction in a given model.

We are interested in the effect of unconstrained supersymmetric (SUSY) CP violating phases on the inclusive decay BR($B \rightarrow X_d\gamma$). We will be working in the context of the effective SUSY model proposed in [16]. Such a model allows one to consider the full impact of the phases on the rare decays of B mesons, while simultaneously satisfying the stringent bounds on the Electric Dipole Moments of the electron and neutron. Such phases may be crucial for generating the observed matter-antimatter asymmetry in the universe [17].

Our work is organized as follows. In section 2 we introduce the decays $b \rightarrow d\gamma$ and $b \rightarrow s\gamma$. In section 3 we outline our approach to calculate the CP asymmetries, while section 4 presents the numerical results. Finally, section 5 contains our conclusions.

2 The decays $b \rightarrow d\gamma$ and $b \rightarrow s\gamma$

Much theoretical study has been devoted to the decay $b \rightarrow s\gamma$ due to its sensitivity to physics beyond the SM [18]. Exclusive channels ($B \rightarrow K^*\gamma$ etc.) and the inclusive channel have been measured at CLEO, ALEPH, BELLE and BaBar [19]. The related decay $b \rightarrow d\gamma$ has received less attention although is expected to be observed at the B factories, at least in some exclusive channels.

Ref. [10] calculated $\text{BR}(B \rightarrow X_d\gamma)$ in the context of the SM. It was shown that the ratio R defined by

$$R = \frac{\text{BR}(B \rightarrow X_d\gamma)}{\text{BR}(B \rightarrow X_s\gamma)} \quad (2)$$

is expected to be in the range $0.017 < R < 0.074$, corresponding to $\text{BR}(B \rightarrow X_d\gamma)$ of order $10^{-5} \rightarrow 10^{-6}$. With 10^8 $B\bar{B}$ pairs expected from the B factories, one would be able to produce $10^2 \rightarrow 10^3$ $b \rightarrow d\gamma$ transitions. In the ratio R most of the theoretical uncertainties cancel, and hence R may provide a theoretically clean way of extracting the ratio $|V_{td}/V_{ts}|$.

The CP asymmetry (\mathcal{A}_{CP}), defined by¹

$$\mathcal{A}_{CP}^{d\gamma(s\gamma)} = \frac{\Gamma(\bar{B} \rightarrow X_{d(s)}\gamma) - \Gamma(B \rightarrow X_{\bar{d}(\bar{s})}\gamma)}{\Gamma(\bar{B} \rightarrow X_{d(s)}\gamma) + \Gamma(B \rightarrow X_{\bar{d}(\bar{s})}\gamma)} = \frac{\Delta\Gamma_{d(s)}}{\Gamma_{d(s)}^{tot}} \quad (3)$$

is expected to lie in the range $-7\% \leq \mathcal{A}_{CP}^{d\gamma} \leq -35\%$ in the SM [10], where the uncertainty arises from varying ρ and η in their allowed regions. Also included is the scale dependence (μ_b) of $\mathcal{A}_{CP}^{d\gamma}$ which occurs from varying $m_b/2 \leq \mu_b \leq 2m_b$. For definiteness we fix $\mu_b = 4.8$ GeV, and find $-5\% \leq \mathcal{A}_{CP}^{d\gamma} \leq -28\%$. Therefore $\mathcal{A}_{CP}^{d\gamma}$ is much larger than $\mathcal{A}_{CP}^{s\gamma}$ ($\leq 0.6\%$). By estimating values for detection efficiencies, it has been argued in [14] that $\mathcal{A}_{CP}^{d\gamma}$ may be statistically more accessible than $\mathcal{A}_{CP}^{s\gamma}$, at least in the context of the SM. This analysis assumes that $B \rightarrow X_d\gamma$ can be clearly isolated from $B \rightarrow X_s\gamma$.

However, it is known that isolating the signal $B \rightarrow X_d\gamma$ would be an experimental challenge since $B \rightarrow X_s\gamma$ constitutes a serious background. [14] has suggested several ways to overcome this problem, e.g. demanding a higher energy cut on γ , since γ from $B \rightarrow X_d\gamma$ will be more energetic than that from $B \rightarrow X_s\gamma$. Energy cuts can be used to separate $b \rightarrow s\gamma$ events from charmed background since there is a high photon energy region that is inaccessible to charmed states because of the mass of the charm quarks. This method is not feasible for extracting $b \rightarrow d\gamma$ events from a $b \rightarrow s\gamma$ sample. Although the strange quark mass is larger than the down quark mass, the respective lightest hadronic single particle final states, K^* and ρ , have almost the same mass (they actually overlap strongly). The lightest multi-particle states are $K\pi$ and $\pi\pi$, respectively, but even here effects such as bound state effects (neglected in [14]) smear the spectra out over regions of the order of 200 MeV. These effects constitute one of the major theoretical uncertainties in the extraction of $\text{BR}(B \rightarrow X_s\gamma)$ from the measured part of the spectrum, and they make a separation of $b \rightarrow d\gamma$ and $b \rightarrow s\gamma$ via energy cuts impossible. A comparison of the photon energy spectra for $b \rightarrow s\gamma$ and $b \rightarrow d\gamma$ was made in [9], and showed that the photon spectra for both decays are very similar.

¹ Note that our definition \mathcal{A}_{CP} contains a relative minus sign compared to that used in [10],[12], [15]

A more promising approach constitute exclusive channels [1, 21, 22]. The improved K/π separation at the B factories may enable the inclusive $B \rightarrow X_d \gamma$ decay to be reconstructed by summing over the relevant exclusive channels as done by CLEO in the measurement of $B \rightarrow X_s \gamma$. [14] suggested using a semi-inclusive sample of $B \rightarrow \gamma + n\pi$ decays with a maximum of n (say 5) mesons together with a corresponding measurement of $B \rightarrow \gamma + K + (n-1)\pi$. The ratio of the widths of the semi-inclusive samples would enable the total inclusive rate to be deduced to a very good approximation. Although the extraction of the branching ratio for $b \rightarrow d\gamma$ from exclusive channels might suffer additional uncertainties with respect to $b \rightarrow s\gamma$ [6] the asymmetry should not be affected by these.

If $\mathcal{A}_{CP}^{d\gamma}$ and $\mathcal{A}_{CP}^{s\gamma}$ cannot be separated, then only their sum can be measured. In the context of the SM (with $m_s = m_d = 0$) the unitarity of the CKM matrix ensures that the sum is zero [20, 23]. This relation holds only for the short distance contribution, which is expected to be dominant (c.f. introduction). In the presence of new physics such a cancellation does not occur, as will be shown in section 4. As stressed earlier, a reliable prediction of $\mathcal{A}_{CP}^{d\gamma}$ in a given model is necessary since it contributes to the measurement of $\mathcal{A}_{CP}^{s\gamma}$. The CLEO result is sensitive to a weighted sum of CP asymmetries, given by:

$$\mathcal{A}_{CP}^{exp} = 0.965\mathcal{A}_{CP}^{s\gamma} + 0.02\mathcal{A}_{CP}^{d\gamma} \quad (4)$$

The latest measurement stands at $-27\% < \mathcal{A}_{CP}^{exp} < 10\%$ (90% c.l.) [15]. The small coefficient of $\mathcal{A}_{CP}^{d\gamma}$ is caused by the smaller $\text{BR}(B \rightarrow X_d \gamma)$ (assumed to be 1/20 that of $\text{BR}(B \rightarrow X_s \gamma)$) and inferior detection efficiencies, but may be partly compensated by the larger value for $\mathcal{A}_{CP}^{d\gamma}$. We shall see that there can be both constructive and destructive interference between the two terms in eq. (4). These effects will be especially important for measurements in future high luminosity runs of B factories, in which the precision is expected to reach a magnitude where the $b \rightarrow d\gamma$ contribution becomes crucial. For integrated luminosities of 200 fb^{-1} (2500 fb^{-1}) [24] anticipates a precision of 3%(1%) in the measurement of \mathcal{A}_{CP}^{exp} .

3 Direct CP Asymmetry in $B \rightarrow X_{d,s} \gamma$

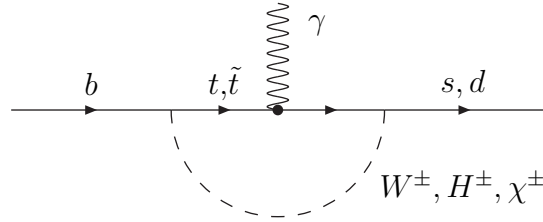
In this paper we explore the effect of CP violating SUSY phases on the direct CP asymmetry of the inclusive decay $B \rightarrow X_{d(s)} \gamma$. We will show that the asymmetry $\mathcal{A}_{CP}^{d\gamma}$ may be quite different from the SM prediction in a wide region of parameter space consistent with experimental bounds from the Electric Dipole Moment (EDM) and $\text{BR}(B \rightarrow X_s \gamma)$.

In our analysis we adapt the “effective SUSY” model, proposed in [16]. This model permits unrestricted SUSY phases and evades the electric dipole moment (EDM) constraint by invoking large masses (of order 20 TeV) for the first two generations of sfermions, thus maintaining their contribution to the EDMs within the experimental limits. The third generation sfermions are allowed to be relatively light ($\leq 1 \text{ TeV}$) with large phases in μ and the soft breaking term A_t . Such an approach has been used on several occasions [25], [26] in order to study the maximum impact of SUSY phases on rare B decays. It was pointed out in [27] that the third generation squarks may contribute to the EDMs via non-negligible two loop diagrams, and we include this constraint in our analysis.

Previous work on the magnitude of $\mathcal{A}_{CP}^{d\gamma}$ in models beyond the SM include multi-Higgs doublet models [13, 14], a Left-Right symmetric model [11] and the MSSM without SUSY

phases [12]. A common feature to all these analyses is the possibility of $\mathcal{A}_{CP}^{d\gamma}$ being of opposite sign to that of the SM, which would be a clear signal of new physics. Ref. [12] took A_t and μ to be real, and thus the only source of CP violation was the CKM phase. They found two phenomenological acceptable regions, corresponding to $2\% \leq \mathcal{A}_{CP}^{d\gamma} \leq 21\%$ and $-45\% \leq \mathcal{A}_{CP}^{d\gamma} \leq -5\%$. It is instructive to consider the impact of unconstrained SUSY phases on the inclusive decay $B \rightarrow X_d \gamma$ by taking A_t and μ complex. The same approach has been used in Ref.[25], and it was shown that $\mathcal{A}_{CP}^{s\gamma}$ may lie in the range $-16\% \leq \mathcal{A}_{CP}^{s\gamma} \leq 16\%$. Other authors [28] have considered a variety of SUSY models with additional theoretical assumptions, resulting in lower values for the maximum value of $\mathcal{A}_{CP}^{s\gamma}$. The study of $b \rightarrow d\gamma$ in these models will be considered in future work [29].

We now briefly outline our approach for the calculation of $\mathcal{A}_{CP}^{d(s)\gamma}$. We assume that flavour changing neutral current vertices induced by the gluino and neutralino are absent. Therefore to lowest order, the decay at quark level proceeds via the following diagrams, where the photon may be emitted from any charged line:



The effective Hamiltonian for $b \rightarrow d\gamma$ is given by

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{td}^* V_{tb} \sum_{i=1}^8 C_i(\mu_b) Q_i(\mu_b) \quad (5)$$

where $Q_i(\mu_b)$ is the current density operator for the $\Delta B = 1$ transition and $C_i(\mu_b)$ is its Wilson coefficient. The relevant operators for $b \rightarrow d\gamma$ decay are given by

$$\begin{aligned} Q_2 &= \bar{d}_L \gamma^\mu c_L \bar{c}_L \gamma^\mu b_L, \\ Q_7 &= \frac{e}{16\pi^2} m_b \bar{d}_L \sigma^{\mu\nu} b_R F_{\mu\nu}, \\ Q_8 &= \frac{g_s}{16\pi^2} m_b \bar{d}_L \sigma^{\mu\nu} T^a b_R G_{\mu\nu}^a. \end{aligned} \quad (6)$$

The analogous formulae for the $b \rightarrow s\gamma$ decay can be obtained from Eqs.(5) and (6) by making the replacement $d \rightarrow s$.

The asymmetry $\mathcal{A}_{CP}^{d(s)\gamma}$ can be written as:

$$\begin{aligned} \mathcal{A}_{CP}^{d(s)\gamma} &= \frac{10^{-2}}{|C_7|^2} \left(1.17 \times \text{Im}[C_2 C_7^*] - 9.51 \times \text{Im}[C_8 C_7^*] + 0.12 \times \text{Im}[C_2 C_8^*] \right. \\ &\quad \left. - 9.40 \times \text{Im}[\epsilon_{d(s)} C_2 (C_7^* - 0.013 C_8^*)] \right) \end{aligned}$$

$$\begin{aligned}
&= \frac{1.1}{(1 + \text{Re}[\xi_7])^2 + (\text{Im}[\xi_7])^2} [0.54 \text{Im}[\xi_7] - 0.25 \text{Im}[\xi_8] - 0.19 \text{Im}[\xi_7^* \xi_8] \\
&\quad + 3.21 \text{Im}[\epsilon_{s(d)}(1 + 0.65\xi_7^* + 0.04\xi_8^*)]]
\end{aligned} \tag{7}$$

where $\xi_{7,8} = (C_{7,8} - C_{7,8}^{SM})/C_{7,8}^{SM}$. $C_{7,8}$ include the total contribution while $C_{7,8}^{SM}$ contain only the Standard Model one. Here we use $C_7^{SM} = -0.30$ and $C_8^{SM} = -0.14$.

In the SM since all the Wilson coefficients are real, the only contribution comes from the final term, which corresponds to the CKM phase in $\epsilon_x = V_{ux}^* V_{ub}/V_{tx}^* V_{tb}$.

The branching ratios in terms of the new physics contributions are given by

$$\begin{aligned}
\text{Br}(B \rightarrow X_s \gamma) &= \frac{|V_{ts}^* V_{tb}|^2}{|V_{cb}|^2} \frac{6\alpha_{em}}{\pi f(z)} |C_7|^2 \text{Br}(B \rightarrow X_c e \bar{\nu}_e), \\
&\simeq (3.48 \pm 0.31) \times 10^{-4} \left[(1 + \text{Re}[\xi_7])^2 + (\text{Im}[\xi_7])^2 \right],
\end{aligned} \tag{8}$$

$$\text{Br}(B \rightarrow X_d \gamma) = \lambda^2 [(1 - \rho)^2 + \eta^2] \text{Br}(B \rightarrow X_s \gamma). \tag{9}$$

The dominant contribution to the decay comes from C_7 evaluated at the scale m_b , which may be divided into contributions from W^\pm, H^\pm and χ^\pm respectively:

$$C_7 = C_7^W + C_7^H + C_7^\chi \tag{10}$$

Both C_7^W and C_7^H are purely real, while C_7^χ may possess an imaginary part. We will use the leading order expressions for C_7 which may be found in [30]. Although higher order corrections to C_7^W are available, the corrections to C_7^H and C_7^χ are only valid in certain limiting cases which are not generally applicable [31]. Therefore to be consistent to a given order we limit ourselves to the leading order expressions for the Wilson coefficients. Such an approach has also been adopted in [14] and [25]. The magnitude of $|C_7|$ is constrained by measurements of the branching ratio of $b \rightarrow s\gamma$, and so we only consider points in parameter space that satisfy $0.2 \leq |C_7(m_b)| \leq 0.38$.

In effective supersymmetry the main contribution to the EDMs of the electron and neutron comes from the two-loop constraint induced by Barr-Zee diagrams involving the Higgs pseudoscalar (A^0) and the third generation squarks [27]. Since the neutron EDM has large hadronic uncertainties, we only consider the upper bound of the electron EDM in our analysis. For large values of $\tan\beta$ this contribution may exceed the present experimental bounds. We have checked that the region $\tan\beta \leq 30$ comfortably satisfies this EDM constraint even for a light \tilde{t}_1 (≤ 200 GeV). In particular, larger values of the Higgs pseudoscalar mass ($M_A \geq 400$ GeV) induce enough suppression to allow a sizeable parameter space with $\tan\beta \geq 30$. We shall see that the full range of values for $\mathcal{A}_{CP}^{d\gamma}$ and $\mathcal{A}_{CP}^{s\gamma}$ can be obtained for any value of $\tan\beta \geq 10$, and so such a constraint has little impact on our results.

4 Numerical Results

We vary the (SUSY) parameters in the following range:

	M	M'	$\tan \beta$	m_{H^\pm}	M_Q	M_U	μ	ϕ_μ	A_t	ϕ_A	ρ	η
min	0	0	1	200	0	0	0	0	0	0	-0.1	0.2
max	400	400	30	500	200	200	200	2π	300	2π	0.4	0.5

Here M and M' are respectively the $SU(2)$ and $U(1)$ gaugino soft masses; A_t is the tri-linear soft mass for \tilde{t} , with phase ϕ_A ; M_Q and M_U are the soft masses for the third generation squarks. We respect the direct search lower limits on the masses of \tilde{t}_1 , χ^\pm by discarding generated points that do not pass our cuts of $m_{\tilde{t}_1} > 90$ GeV and $m_{\chi_1^\pm} > 80$ GeV in addition to the cut on C_7 mentioned in Sec. 3. We vary ρ and η in the range allowed by present CKM fits for the SM [3]. Note that in the effective SUSY model one should strictly only include the constraint from $|V_{ub}/V_{cb}|$, which corresponds to varying ρ and η in a semi-circular band in the $\rho - \eta$ plane. This enlarged parameter space has little effect on our graphs, except for Fig.3, which will be commented on below.

If the signal for the inclusive decay can be isolated then a positive asymmetry would be a clear sign of new physics. In Fig. 1 we plot $\mathcal{A}_{CP}^{d\gamma}$ against $m_{\tilde{t}_1}$, which clearly shows that a light \tilde{t}_1 may drive $\mathcal{A}_{CP}^{d\gamma}$ positive, reaching maximal values close to +40%. For \tilde{t}_1 heavier than 250 GeV the $\mathcal{A}_{CP}^{d\gamma}$ lies within the SM range, which is indicated by the two horizontal lines.

We note that our upper limit of +40% is larger than the maximum value of 21% attained in [12]. The inclusion of the SUSY phases has joined and expanded the two phenomenological regions found in [12], allowing CP asymmetries in the continuous region $-40\% \leq \mathcal{A}_{CP}^{d\gamma} \leq 40\%$. In Fig. 2 we show that the large positive asymmetries can be found anywhere in the interval $5 \leq \tan \beta \leq 30$, which is the region where the EDM constraint in [27] is comfortably satisfied.

If the signals from $b \rightarrow s\gamma$ and $b \rightarrow d\gamma$ cannot be isolated then one must consider a combined signal. In Fig. 3 we plot $\mathcal{A}_{CP}^{d\gamma}$ against $\mathcal{A}_{CP}^{s\gamma}$. The maximum values for $\mathcal{A}_{CP}^{s\gamma}$ agree with those found in [25]. It can be seen that there is an inaccessible region and the asymmetries can never simultaneously be zero e.g. for $\mathcal{A}_{CP}^{d\gamma} \approx 0$, $|\mathcal{A}_{CP}^{s\gamma}| \geq 3\%$. This can be explained from the fact that $\mathcal{A}_{CP}^{d\gamma} \approx 0$ would require C_7 to have a sizeable imaginary part in order to cancel the large negative contribution from ϵ_d . The corresponding effect on $\mathcal{A}_{CP}^{s\gamma}$ would be to cause a sizeable deviation from its small SM value. Fig. 3 shows that both $\mathcal{A}_{CP}^{s\gamma}$ and $\mathcal{A}_{CP}^{d\gamma}$ can have either sign, resulting in constructive or destructive interference in eq. (4). If only the $|V_{ub}/V_{cb}|$ constraint is included in the CKM fits, the enlarged parameter space for ρ and η allows much smaller asymmetries for $\mathcal{A}_{CP}^{d,s\gamma}$. This is because smaller values of η are now allowed, which reduces the SM contribution to $\mathcal{A}_{CP}^{d,s\gamma}$. The choice of $\eta \rightarrow 0$ would correspond to points in the previously inaccessible region.

In Fig. 4 we plot $\Delta\Gamma_d + \Delta\Gamma_s$ (defined in eq. (3)) against $\text{Im}(C_7)$. In the SM (as explained in Section 2) this sum would be exactly zero in the limit $m_s = m_d = 0$ (neglecting the small long distance contribution). From Fig. 4 it can be seen that $\Delta\Gamma_d + \Delta\Gamma_s$ is close to 0 if C_7 is real, the slight deviation being caused by the imaginary parts of the other Wilson coefficients. The effect of a non-zero $\text{Im}(C_7)$ causes sizeable deviations from zero.

In Fig. 5 we plot the $\mathcal{A}_{CP}^{c\gamma}$ (defined in eq. (4)) against $\mathcal{A}_{CP}^{s\gamma}$. The right hand plot shows a magnification of the area around the origin. The coefficient of $\mathcal{A}_{CP}^{d\gamma}$ in eq. (4) assumes that $\text{BR}(b \rightarrow d\gamma) = \text{BR}(b \rightarrow s\gamma)/20$. Since this ratio of BRs is $\sim |V_{td}/V_{ts}|^2$, which in turn is a function of the variables ρ and η , we replace the factor 1/20 by the above ratio of CKM matrix elements. If the contribution from $\mathcal{A}_{CP}^{d\gamma}$ were ignored in eq. (4), then Fig. 5 would be a straight

line through the origin. The $\mathcal{A}_{CP}^{d\gamma}$ contribution broadens the line to a thin band of width $\approx 1\%$, an effect which should be detectable at proposed higher luminosity runs of the B factories.

Note that the width of the line is determined by the amount of $b \rightarrow d\gamma$ admixture in the $b \rightarrow s\gamma$ sample, eq. (3). In the case of the CLEO measurement the admixture of $b \rightarrow d\gamma$ is about 2.5 times less than the “natural” admixture (ratio of the branching ratios). If the experimental analysis can be done with a natural admixture or even a $b \rightarrow d\gamma$ enriched sample, the width of the line would be correspondingly broader. Specifically, for the natural admixture the line would be broadened by a factor of 2.5, making $b \rightarrow d\gamma$ a 2.5% effect. This effect is the same magnitude as the precision attainable with an integrated luminosity of 200 fb^{-1} at the B factories [24]. At this luminosity it will therefore be possible to test the cancellation of the asymmetries as predicted by the SM.

5 Conclusions

We have studied the effect of supersymmetric (SUSY) CP violating phases on the direct CP asymmetry in the inclusive decay $B \rightarrow X_d\gamma$. We have performed our calculation in the effective SUSY Model, which allows unrestricted SUSY phases without violating the stringent constraints from the electron EDM. Although such a decay contains a large background from $B \rightarrow X_s\gamma$, it may exhibit large direct CP violation in the context of the Standard Model (SM) and its extensions.

In the SM the CP asymmetry $\mathcal{A}_{CP}^{d\gamma}$ is expected to lie in the range $-5\% \leq \mathcal{A}_{CP} \leq -28\%$. A previous analysis in the context of the MSSM in the absence of SUSY phases found two phenomenologically acceptable regions in SUSY parameter space corresponding to asymmetries of $-45\% \leq \mathcal{A}_{CP} \leq -5\%$ and $2\% \leq \mathcal{A}_{CP} \leq 21\%$. The latter would constitute a clear signal of physics beyond the SM. We have shown that the inclusion of phases in the SUSY breaking parameters joins and expands these regions to allow CP asymmetries in the continuous region $-40\% \leq \mathcal{A}_{CP} \leq 40\%$, where the exact boundaries depend strongly on the bounds for C_7 that are imposed. The largest values for the positive asymmetry occur when the stop is lighter than 200 GeV. Asymmetries of this magnitude are expected to be within the reach of the B factories BELLE and BaBar.

If the inclusive decay $B \rightarrow X_d\gamma$ cannot be isolated from $B \rightarrow X_s\gamma$ then one must consider a combined signal. In the SM the sum of the dominant short distance contributions is identically zero (for $m_d = m_s = 0$), although such a cancellation does not occur in the effective SUSY model since C_7 may possess an imaginary part. We have studied the correlation between $\mathcal{A}_{CP}^{d\gamma}$ and $\mathcal{A}_{CP}^{s\gamma}$, showing that there may be both constructive and destructive interference. The contribution of $B \rightarrow X_d\gamma$ to the combined signal \mathcal{A}_{CP}^{exp} is suppressed by a branching ratio factor $|V_{td}/V_{ts}|^2$, but may be partly compensated by its potentially larger asymmetry. These results will be particularly important at proposed high luminosity runs of the B factories, in which the experimental error in the measurement of \mathcal{A}_{CP}^{exp} is expected to reach a level comparable to the magnitude of the $B \rightarrow X_d\gamma$ contribution.

Acknowledgments

A.A and S.R wish to thank K. Hagiwara for his encouragement and the participants of the poster session at BCP4 for useful discussions. A.A. and S.R were supported by the Japan Society for the Promotion of Science (JSPS).

YYK wishes to thank H.Y.Cheng for his encouragement and S. Baek for useful comments. The work of YYK was supported by the National Science Council of R.O.C. under the Grant No. NSC-90-2811-M-002 on CP violation in B meson Physics.

References

- [1] Report of the BaBar Physics Workshop.
- [2] Plenary Talks at ICHEP2000, Osaka, by BaBar Collaboration (hep-ex/0011024), Belle Collaboration, CLEO Collaboration, <http://ichep2000.hep.sci.osaka-u.ac.jp/plenary.html>
- [3] M. Ciuchini *et al*, hep-ph/0012308
- [4] A. Ali and G. Hiller, Eur. Phys. J. **C8** (1999) 619.
- [5] A. Ali and V.M. Braun, Phys. Lett. **B359** (1995) 223; A. Khodjamirian, G. Stoll and D. Wyler, Phys. Lett. **B358** (1995) 129.
- [6] J. F. Donoghue, E. Golowich and A. A. Petrov, Phys. Rev. D **55**, 2657 (1997)
- [7] CLEO Collaboration, T.E. Coan *et al* Phys. Rev. Lett, **84** (2000) 5283.
- [8] M. Nakao (BELLE Collaboration), Talk given at ICHEP2000, Osaka. BELLE-CONF-0003 (<http://bsunsrv1.kek.jp/conferences/papers/>)
- [9] A. Ali and C. Greub, Phys. Lett. **B287** (1992) 191.
- [10] A. Ali, H. Asatrian and C. Greub, Phys. Lett. **B429** (1998) 87.
- [11] H.M. Asatrian, G.K. Yeghiyan and A.N. Ioannissian, Phys. Lett. **B399** (1999) 148.
- [12] H.H. Asatrian and H.M. Asatrian, Phys. Lett. **B460** (1999) 148.
- [13] H.H. Asatrian, H.M. Asatrian and G.K. Yeghiyan, hep-ph/0012085
- [14] K. Kiers, A. Soni and G-H. Wu, Phys. Rev. **D62** (2000) 1116004.
- [15] CLEO Collaboration, T.E. Coan *et al*, hep-ex/0010075.
- [16] A.G. Cohen, D.B. Kaplan and A.E. Nelson, Phys. Lett. **B388** (1996) 588.
- [17] M. Carena and C.M. Wagner, hep-ph/9704347; M.P. Worah, Phys. Rev. Lett. **79** (1997) 3810; J.M. Cline, M. Joyce and K. Kainulainen, Phys. Lett. **B417** (1998) 79; M. Carena, M. Quiros and C.E.M. Wagner, Nucl. Phys. **B524** (1998) 3; G.M. Cline and G.D. Moore, Phys. Rev. Lett. **79** (1998) 3315.

- [18] M. Misiak, hep-ph/0009033, Talk at ICHEP2000, Osaka, and references therein; J. Hewett, hep-ph/9406302.
- [19] CLEO Collaboration, Phys. Rev. Lett. **74** (1995) 2885; hep-ex/9908022.; ALEPH Collaboration, Phys. Lett. **B429** (1998) 169; BELLE Collaboration (see [8]).
- [20] A.L. Kagan and M. Neubert, Phys. Rev. **D58** (1998) 094012.
- [21] A. Ali, hep-ph/0101154.
- [22] A. Ali, L.T. Handoko and D. London, Phys. Rev. **D63** (2000) 014014
- [23] J.M. Soares, Nucl. Phys. **B367** (1991) 575.
- [24] J. Alexander, Talk given at BCP4, Ise, Japan, February 2001.
- [25] S. Baek and P. Ko, Phys. Rev. Lett. **83** (1999) 488; Phys. Lett. **B462** (1999) 95.
- [26] A.G. Cohen, D.B. Kaplan, F. Lepeintre and A.E. Nelson, Phys. Rev. Lett. **78** (1997) 2300; G. Barenboim and M. Raidal, Phys. Lett. **B457** (1999) 109; F. Kruger and J.C. Romao, Phys. Rev. **D62** (2000) 034020.
- [27] D. Chang, W.Y. Keung and A. Pilaftsis, Phys. Rev. Lett. **82** (1999) 900; errata *ibid* **83** (1999) 3972.
- [28] T. Goto, Y.Y. Keum, T. Nihei, Y. Okada, Y. Shimizu, Phys. Lett. **B460** (1999) 333; M. Aoki, G.C. Cho and N. Oshimo, Phys. Rev. **D60** (1999) 035004; Nucl. Phys. **B554** (1999) 50; C.K. Chua, X.E. He and W.S. Hou, Phys. Rev. **D60** (1999) 014003; Y.G. Kim, P. Ko and J.S. Lee, Nucl. Phys. **B544** (1999) 64.
- [29] A.G. Akeroyd, Y.Y. Keum and S. Recksiegel, work in progress
- [30] A. J. Buras, M. Misiak, M. Munz and S. Pokorski, Nucl. Phys. **B424** (1994) 374 [hep-ph/9311345].
- [31] M. Ciuchini, G. Degrassi, P. Gambino and G.F. Giudice, Nucl. Phys. **B527** (1998) 21; Nucl. Phys. **B534** (1998) 3; P. Ciafaloni, A. Romanino and A. Strumia, Nucl. Phys. **B524** (1998) 361; F.M. Borzumati and C. Greub, Phys. Rev. **D58** (1998) 074004; Phys. Rev. **D59** (1999) 057501.

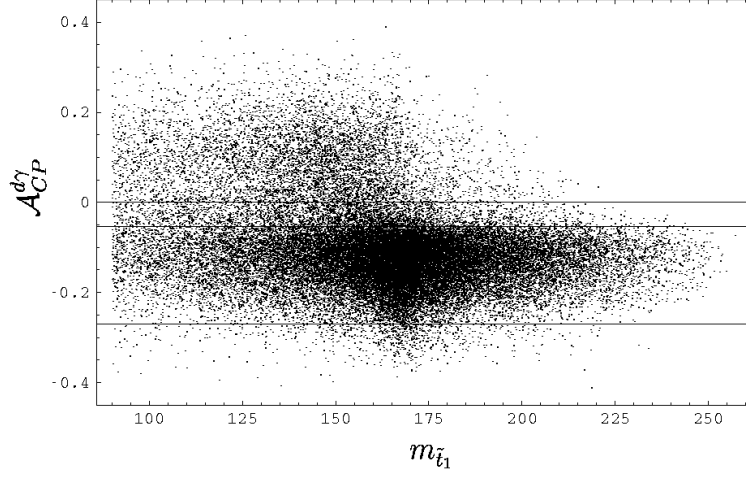


Figure 1: $\mathcal{A}_{CP}^{d\gamma}$ against $m_{\tilde{t}_1}$

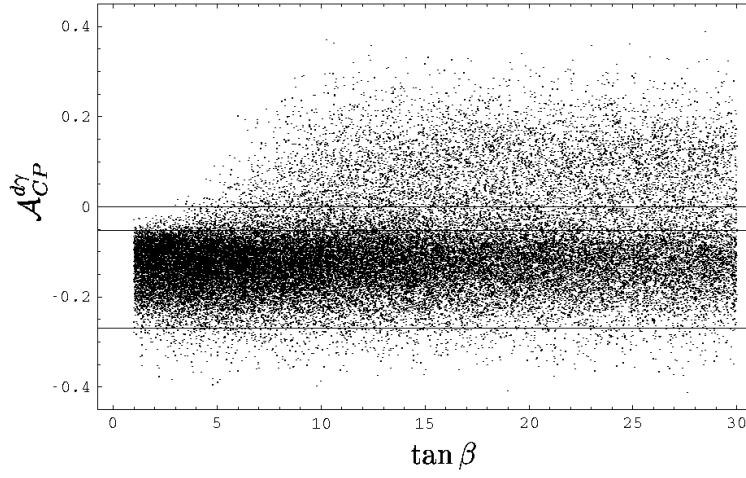


Figure 2: $\mathcal{A}_{CP}^{d\gamma}$ against $\tan \beta$

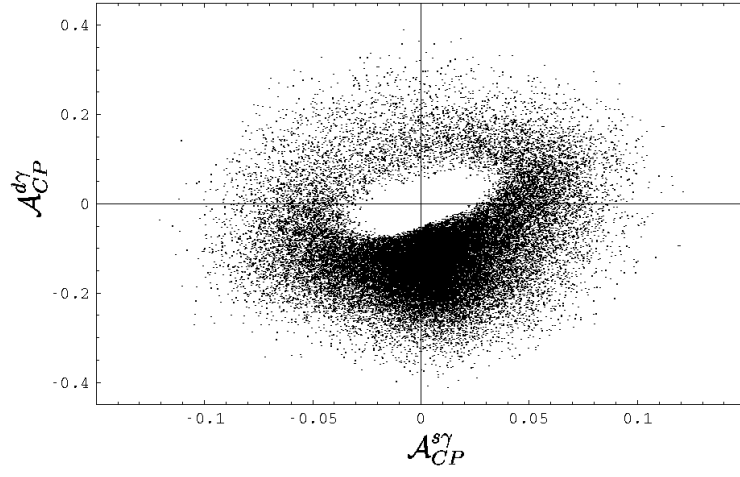


Figure 3: $\mathcal{A}_{CP}^{d\gamma}$ against $\mathcal{A}_{CP}^{s\gamma}$

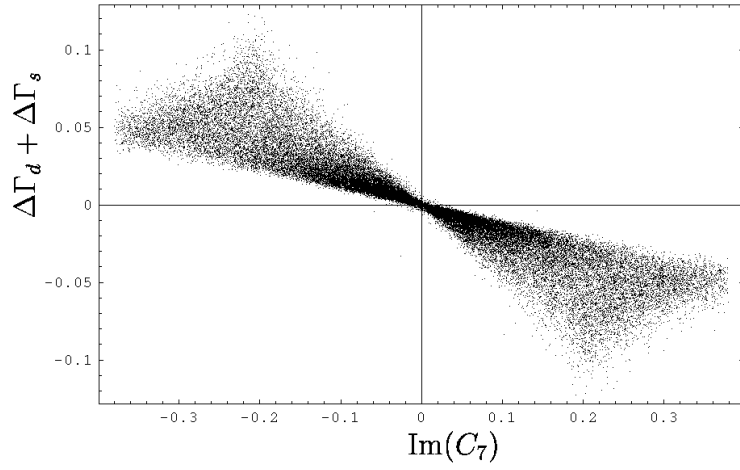


Figure 4: $\Delta\Gamma_d + \Delta\Gamma_s$ against $\text{Im}(C_7)$

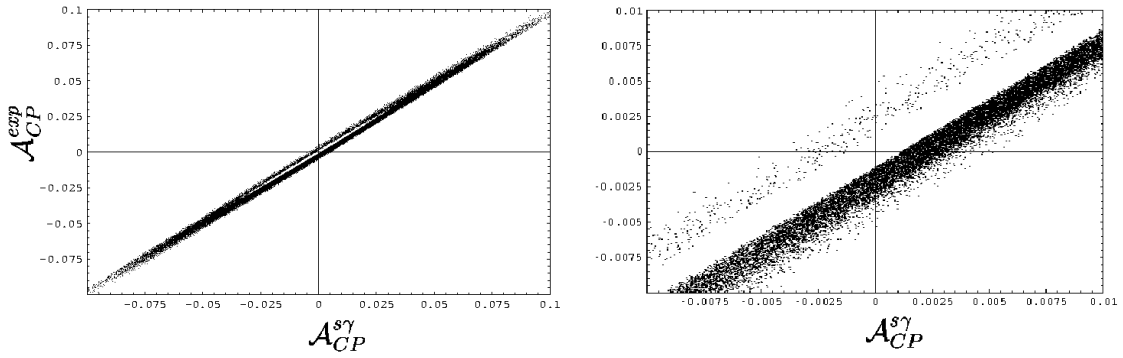


Figure 5: Combined asymmetry measured by CLEO (\mathcal{A}_{CP}^{exp}) against $\mathcal{A}_{CP}^{s\gamma}$